FUSION BONDING OF CARBON FABRIC REINFORCED POLYPHENYLENE SULPHIDE BY HOT-TOOL WELDING

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SUMMARY

In this paper, it is assessed whether the 'hot-tool' welding process is suited for welding fibre reinforced thermoplastics. The quality of the welds is investigated using a short three-point bending test, which is also modelled in finite element software to see if a suitable distribution of interlaminar shear stresses is present.

Keywords: Hot-Tool welding, Fusion Bonding, Thermoplastic, Carbon, FEM

INTRODUCTION

An ideal structure would be designed without joints, since joints are potential sources of weakness and additional weight. In practice, however, the maximum size of a component is generally limited by the manufacturing processes. Moreover, demands such as inspection, accessibility, repair and of course transportation and assembly result in the fact that load-bearing joints cannot be avoided. This fact does not change when designing with fibre-reinforced composites; joints can be drastically reduced, but they will always be a part of a structure. Adhesive bonding is inherently preferable to mechanical fastening because of the continuous connection, avoiding large stress concentrations induced by each discrete fastener hole. However, extensive surface preparation and long curing times make adhesive bonding labour intensive. Moreover, the need for recyclability incites more and more manufacturers to choose materials and bonding systems which allow for recycling, excluding most thermosetting composites and adhesives.

Therefore, in recent years, the interest is growing in welding processes for thermoplastic composites, since (i) thermoplastics are difficult to bond because of their chemical inertness and (ii) the welding processes can reduce overall manufacturing cost and are expected to replace traditional assembly methods, such as adhesive and solvent bonding, mechanical fastening and co-consolidation bonding [1]. The fusion bonding of pure thermoplastics is already a well known and commonly applied production process, but the process parameters cannot be extrapolated to the welding of fibre-reinforced thermoplastics, since the reinforcement has a large influence: the material is no longer isotropic, head conduction is influenced … In general, these fusion bonding techniques can be categorised in three groups [1]: (i) frictional welding, including ultrasonic welding [2, 3]; (ii) electromagnetic welding, including resistance welding [4, 5, 6,] and induction welding [7, 8] and (iii) thermal welding, including infrared welding [9] and hot-tool welding.

In this manuscript, the hot-tool welding process is considered as fusion bonding technique for a carbon fibre reinforced polyphenylene sulphide. This technique has some interesting advantages, for instance: dissimilar thermoplastics can be welded, the temperature of the molten interfaces can be accurately controlled, surface inaccuracies can be taken into account during the process and it can handle complex geometries [1]. Furthermore, it is a relatively cheap process, since it does not require expensive machinery, as is the case for friction- and ultrasonic welding [1].

To evaluate the quality of the weld, a short-beam bending test, as described in the ASTM D2344/D 2344M '*Standard Test Method for Short-Beam Strength of Polymer Matrix Composite Materials and Their Laminates'* is considered. This test has the advantage that it requires a lot less material than for the lap shear or mode I DCB test and it is a very simple test; force and displacement already give plenty of information. However, to verify that this test setup indeed induces an interesting stress distribution in the bond, the test setup is modelled in the finite element software ABAQUS™.

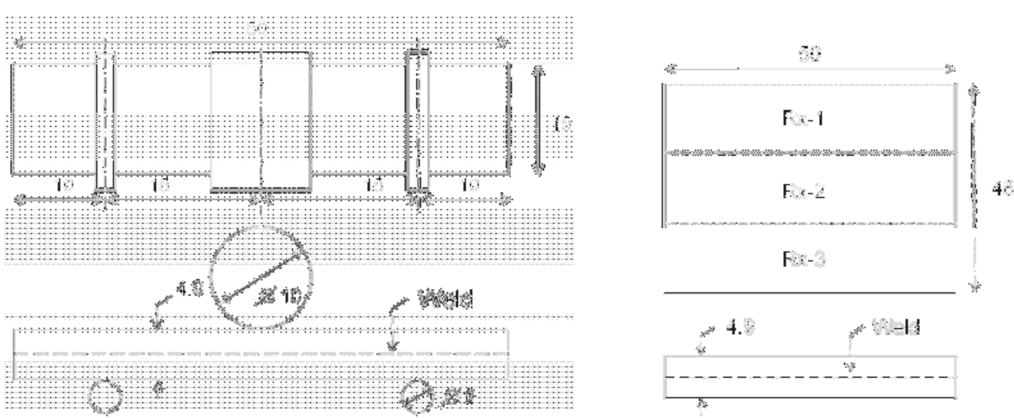
In the next paragraph, the used materials and methods are discussed. This is followed by an overview of the experiments, after which the finite element modelling of the bending setup is given. Finally, some conclusions are drawn.

MATERIALS AND METHODS

Composite Material

The material used for the experiments was a 5-harness satin-weave carbon fabric-reinforced polyphenylene sulphide (PPS). The carbon PPS plates were hot pressed, one stacking sequence was used for this study, namely $[(0^o,90^o)]_{2s}$ where $(0^o,90^o)$ represents one layer of fabric.

The test coupons were sawn with a water-cooled diamond saw; the dimensions of the specimens are shown in Figure 1. The dimensions of the welded specimen are chosen so that from each weld, three bending coupons can be cut.



(a) Bending specimen (b) Welded specimen

Figure 1 Dimensions of the used specimens in millimetres.

To evaluate the strength, the short beam strength, as mentioned in the ASTM D2344/D 2344M '*Standard Test Method for Short-Beam Strength of Polymer Matrix Composite Materials and Their Laminates'* is calculated using Equation 1:

$$\tau^{sbs} = 0.75\frac{P_m}{bh} \qquad [\text{MPa}] \tag{1}$$

where τ^{sbs} is the short-beam strength [MPa], P_m is the maximum load observed during the test [N], b is the width of the specimen [mm] and h is the height of the specimen [mm].

Equipment

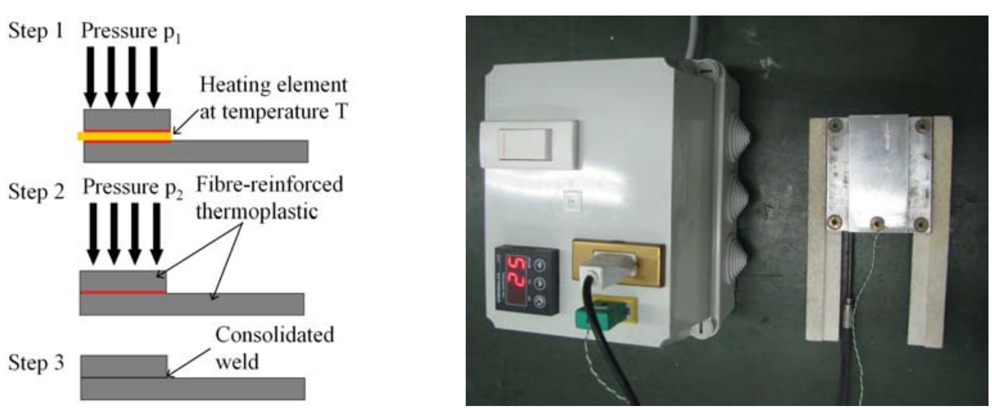
All bending tests were performed on an electromechanical INSTRON 5800R tensile testing machine with a FastTrack 8800 digital controller and a load cell of ±10kN. The quasi-static bending tests were displacement-controlled with a speed of 2 mm/min.

For the registration of the data, a combination of a National Instruments NI-USB-6251 data acquisition card and the SCB-68 pin shielded connecter were used. The load and displacement, given by the FastTrack controller, as well as the temperature from the thermocouple were sampled on the same time basis.

EXPERIMENTS AND DISCUSSION

Welding Process

The fusion bonding process of choice is the 'hot-tool welding', of which the principle is illustrated in Figure 2 (a). The two surfaces to be welded are pushed against a heating element (step 1) and once the temperature is high enough, the two parts are pressed against one another with sufficient force (step 2). If necessary, extra filling material (thermoplastic sheets, reinforcement…) can be added to the weld, but this was not considered for this research. Both the heating element and the control unit are shown in Figure 2 (b).



(a) Principle of hot-tool welding (b) The control unit and 'hot-tool'

Figure 2 The 'hot-tool' welding process.

The surfaces of the parts to be welded make contact with the upper and lower contact plate respectively and the heat is generated using a heating resistor with embedded thermocouple. The power of the resistor is controlled with the separate control unit, which takes the temperature into account. With this device, an area of 100 mm x 100 mm can be heated. For this research, an extra plate was added on top of the welding device, so that a contact area of 50 mm wide can be heated, in order to produce the specimens illustrated in Figure 1 (b).

During the welding phase, one can choose to hold the contact pressure constant or to press down until the weld has a certain thickness. For this study, the contact pressure was increased to the desired value and then the displacement was kept constant. Figure 3 illustrates the evolution of the contact pressure and the temperature during welding. The specimen was heated for about 80 seconds at an average temperature of 305 °C. The temperature was set at 310 °C but because of the high thermal conductivity of carbon, a lot of heat was dissipated to the surroundings and to the tensile machine. Since the temperature of the hot-tool is monitored, only the evolution of the temperature during the heating phase is relevant. Since the embedding of a thermocouple in the weld poses some difficulty, there is no information present on the evolution of the temperature during the consolidation.

There is some scatter on the contact pressure, since it is quite difficult to maintain a constant load, even in load-controlled mode. The decrease in contact pressure during consolidation is due to the fact that the pressure pushes the liquid PPS out of the weld. The specimen is removed once the weld is fully solidified.

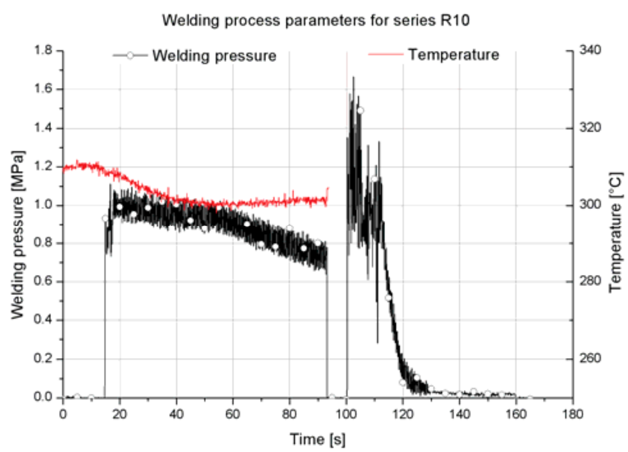


Figure 3 Illustration of the temperature and the welding pressure during the welding process

Bending Experiments

In order to have some sort of reference value, first, some specimens were adhesively bonded with adhesives that gave good results in the past [10]. The results are shown in Figure 4, together with two bending tests on not bonded specimens. These are added to evaluate the bending stiffness when the bond has failed completely. For the adhesively bonded specimens, it can be clearly seen that once a load level around 1800 to 2000 N is reached, corresponding to a short-beam strength of 20.4 MPa, a very brittle interlaminar failure occurs and the force-displacement curve then follows the same trend as the curve from the unbonded specimens. As such, the quality of the weld can also be assessed by the bending stiffens. The load-displacement of the failed bonded specimens lies a little higher than the not bonded specimen, but this is due to the fact that only half of the bond failed, between one outer support and the centre support.

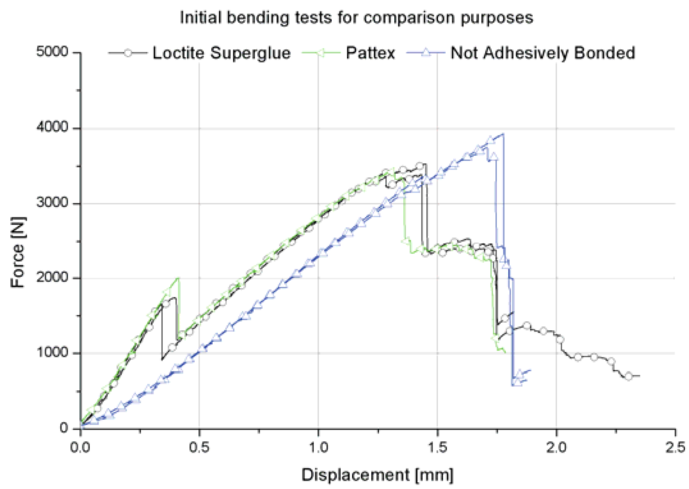


Figure 4 Bending experiments on adhesively bonded specimens

A first series of tests were conducted to evaluate the reproducibility of the quality of the welds of one welded specimen, as illustrated in Figure 1 (b). It could be concluded that there is a good reproducibility, especially with respect to the bending stiffness.

Figure 5 shows several bending experiments on specimens from different welding processes. As can be seen, the reproducibility of the bending stiffness is high. With respect to the failure force, this value of course depends on the welding parameters, but even for a not so successful weld (R4-3) the failure force is still significantly higher than for the adhesively bonded specimens. It can also be noticed that most specimens tend to follow the curve of two separate, not bonded specimens after initial failure, meaning that failure is still quite brittle, although specimen R14-1 shows a very progressive failure.

Finally, Table 1 shows an overview of the welding parameters for the experiments discussed in this paper. The contact pressure during consolidation was always the same as the contact pressure during heating. This pressure was chosen close to 1 MPa, since this is also the consolidation pressure during the hot pressing of the composite plates. In earlier experiments, tests were done with contact pressures up to 3 MPa, but with results inferior to the ones shown here, because al liquid PPS was pushed out of the bond. Therefore, these experiments and settings are not discussed in this manuscript.

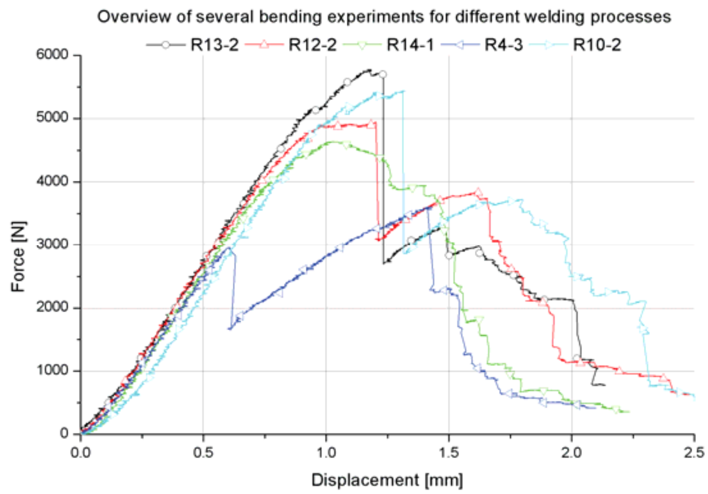


Figure 5 Force-displacement curves for specimens from different welding processes

With respect to the temperature, the melting point of PPS is 280 °C, so temperatures lower were not considered. A temperature higher than 310 °C was too high; on some locations of the welded surface, the PPS started to burn whereas on other locations (for the same weld) the PPS had not even melted. As such, the two specimens could be joined together, but there was no continuous weld and the strength was, of course, inferior. For the successful welds (R10, R12, R13 and R14), an average short-beam strength of 55.5 MPa is achieved.

Table 1 Overview of the welding parameters for the experiments shown in this paper, together with the short-beam strength (Equation 1)

Process	Contact pressure [MPa]	Temperature [°C]	Heating time [s]	τ^{sbs} [MPa]
R4	0.9	290	60	30.02
R10	0.9	300	75	55.53
R12	1	310	20	49.84
R13	1	290	100	58.90
R14	1	300	70	57.68

FINITE ELEMENT MODELLING

The used finite element software was ABAQUS™ Standard 6.8.1 Since only quasi-static tests were performed, there is no need to use an explicit numerical solver and an implicit analysis was used.

The modelling of the three-point bending setup in general has some difficulties. The loading conditions in a beam that is subjected to three-point bending consists of a transverse force V, equal to half of the loading force F, over the entire beam and a bending moment grows linearly until the centre of the beam. How to model a bending setup has already been documented extensively by the authors in [13], so only a short overview is given here.

In order to save calculation time, symmetry is used to model the setup, so only a quarter of the setup is implemented. As a result, the dimensions of the modelled specimen are

4.9 mm x 25 mm x 7.5 mm, the centre and support-roll have a diameter of 10 mm and 2 mm respectively. Also, only a quarter of the centre roll was modelled. For the material, a linear elastic orthotropic material model with the following properties (Table 2) is used. The values for E_{11}, E_{22}, ν_{12} and G_{12} where experimentally determined, whereas the other values where determined using mesoscale analysis.

Table 2 Engineering constants implemented in ABAQUS™.

E_{11} [MPa]	E_{22} [MPa]	E_{33} [MPa]	ν_{12} [-]	ν_{13} [-]	ν_{23} [-]	G_{12} [MPa]	G_{13} [MPa]	G_{23} [MPa]
56000	57000	9700	0.033	0.38	0.38	4175	2904	2902

As was previously mentioned, friction must also be modelled if the simulation is to be as realistic as possible. Therefore, friction formulations were implemented for both the indenting roll and the supporting roll.

Should the entire specimen be modelled with the material parameters, given in Table 2, then it would seem to stiff, since the bond consists of pure PPS. Therefore, to take the effects of the bond into account, the weld is modelled using cohesive contact in the centre of the specimen, where the weld is located. For this area, the properties of pure PPS are used, which are given in Table 3. For the modelling of a cohesive contact, ABAQUS™ only requires the shear properties.

Table 3 Material properties for PPS, used in the cohesive layer

G_{12} [MPa]	G_{13} [MPa]	G_{23} [MPa]
3800	1380	1380

For the simulation of two specimens without a bond, this cohesive contact is replaced by a Lagrange friction formulation with a friction coefficient of 0.2.

The boundary conditions as well as the used mesh are illustrated in Figure 6.

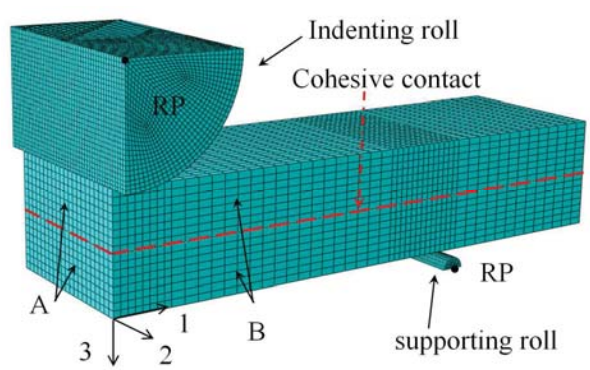


Figure 6 Illustration of the mesh and the boundary conditions for the three-point bending setup with rigid supports.

To model symmetry, the following boundary conditions are applied: on plane A: $U_1 = 0$ and on plane B: $U_2 = 0$. It is not necessary to constrain any rotations, since the used 3D elements do not have rotational degrees of freedom. The reference point of the supporting role is completely fixed. For the indenting roll, the movement along the 1-axis and 2-axis, as well as all rotations are inhibited and a vertical displacement of 1 mm is imposed on the reference point.

Figure 7 shows the results of the finite element simulations. For comparison purposes, a few experiments are added. It can clearly be seen that the simulation with the cohesive contact corresponds very well with both experiments depicted; the bending stiffness is the same. Also, the simulation of the unbonded specimen is very accurate; the bending stiffness also corresponds. Finally, it can again be concluded that once the bond has failed, the force-displacement curve follows that of two unbonded specimens until total failure is reached.

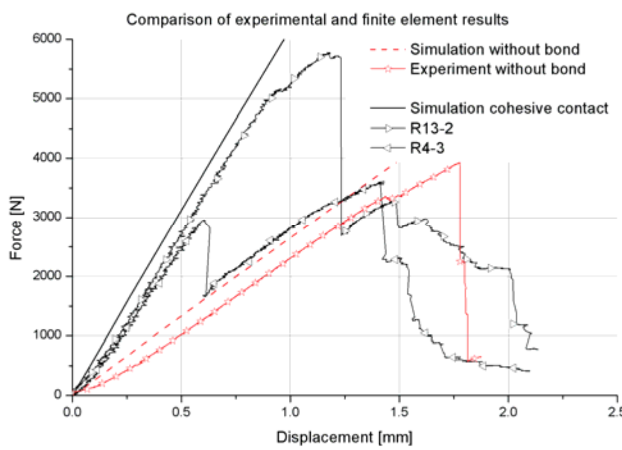


Figure 7 Illustration of both simulated and experimental results for the bending test

Figure 8 shows the interlaminar shear stress distribution through the thickness (a) and for the area with cohesive contact (b), for a displacement of 1 mm. As can be seen, a relatively smooth distribution of the stress is present in the bond, without large local stresses, which occur for instance in a lap shear test or in a Mode I DCB test.

For comparison purposes, the short-beam strength, calculated with Equation 1 is 62.04 MPa; since the simulated bending force at 1 mm is higher than the one achieved in the experiments, the resulting short-beam strength is of course higher than the experimental 55.5 MPa.

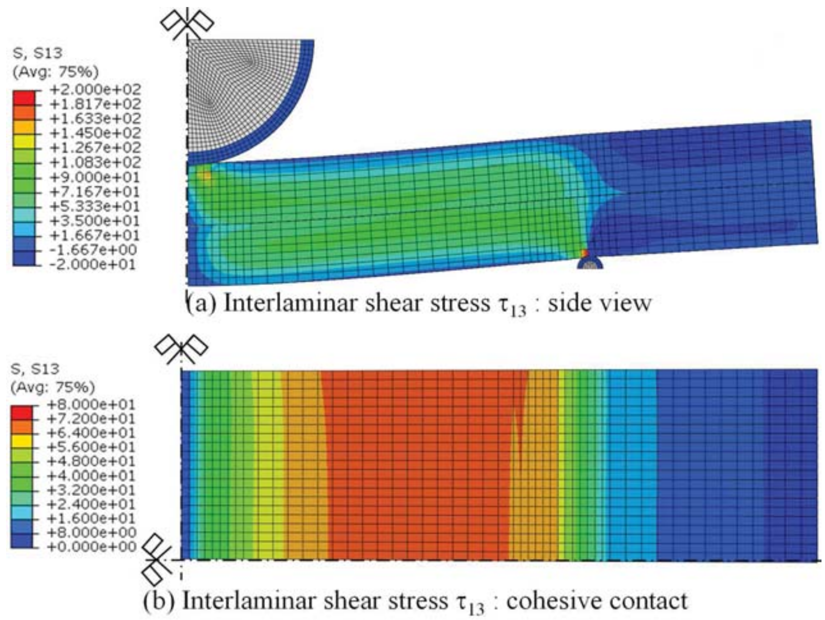


Figure 8 Overview of the interlaminar shear stress distribution at 1 mm defection

CONCLUSIONS

The hot-tool welding process is suited for welding the carbon-fabric reinforced polyphenylene sulphide considered for this research. The interlaminar strength in a short three-point bending test is significantly higher than for adhesively bonded specimens.

For the welding parameters, a temperature between 295 °C and 305 °C in combination with a contact pressure of 1 MPa for about 60 seconds shows best results. Other temperatures resulted in either no melting or burning of the PPS. Lower contact pressures resulted in bad consolidation and higher pressure pushed out all PPS, so no bond could be formed. The time interval is not so narrow, but in general it may be concluded that within the specified range of temperature and pressure, the quality of the weld is mostly dependent on the experience of the operator. For the successful welds, an average short-beam strength of 55.5 MPa was achieved.

Finally, the finite element analysis is able to predict the bending stiffness accurately, both for the bonded specimens and for the two specimens on top of each other. There is a smooth interlaminar shear stress distribution in the short three-point bending test, making it interesting for evaluating bonds between composite specimens.

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